FINAL REPORT

Observations of Internal Waves on an Oceanic Boundary Slope Without a Shelf Region (Hawaiian Islands)

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LONG-TERM GOAL

Our long-term goal is to describe and understand spatial variations of the internal wave field near topography.

OBJECTIVES

Our principal suppositions were that variations in the energy, and the frequency and wavenumber distributions of the internal wave field near topography should be related to spatial differences of environmental parameters such as distance to the boundary, slope magnitude and/or curvature, buoyancy frequency, and so on, as well as to the propensity of the boundary configuration to support trapped oscillations that propagate freely only along the boundary (such as edge and Kelvin waves). Our objective was to test these suppositions with in situ measurements of the current and temperature fields.

The suppositions just described, and the investigative approach described below, arose from published descriptions of the internal wave field in the presence of topography, which paint a sometimes contradictory picture of how the internal wave field is modified by reflection from a sloping boundary. Eriksen (1982) brought to the attention of physical

oceanographers the idea that reflection of internal waves from a sloping bottom results in a re-distribution of energy in wavenumber space producing enhancement of kinetic energy (above that expected for open ocean internal waves) at the critical frequency near the bottom (where the critical frequency, $\omega_c^2 = N^2 \sin^2 \alpha + f^2 \cos^2 \alpha$, where N is the buoyancy frequency, f is the local Coriolis frequency, and α is the bottom slope). [From linear theory, reflection of an internal wave at the critical frequency for a particular slope results in the reflected wave having zero wavelength and infinite energy density.] While this idea was not new, the examination of current and temperature spectra for this phenomenon had not been approached in any systematic way before Eriksen's (1982) outstanding demonstration of the phenomenon.

Curiously, the energy enhancement at the critical frequency did not exist at the continental slope sites presented by Eriksen (1982), though it did exist at Muir Seamount and a near-equatorial, mid-ocean ridge site. One difference between Eriksen's (1982) continental slope site and the others he presented was that the continental slope site had the weakest slope. Combined with Eriksen's (1995, 1998) finding of orders of magnitude enhancement of kinetic energy at the relatively high critical frequency (0.42 cph) over the flank of Fieberling Guyot, the suggestion is clear that the larger slopes result in greater energy enhancement at the critical frequency. But is this the whole story?

Gilbert (1993) conducted an examination of current meter records from 13 sites on the slope and rise off Nova Scotia. He found enhancement of kinetic energy or cross-isobath alignment of motion (another prediction of the linear theory) at the critical frequency only about half of the time. He argued that the lack of critical frequency enhancement was due either to the concavity of the local topography at many sites (such as at the base of the slope) or to the fact that when the slope was weak, such that the critical frequency was close to f, the ambient wave field is composed of waves near their turning latitudes so that their propagation is to the east or west, implying azimuthal incidence angles of around 90 degrees for most of the Scotian slope and rise sites (that is, the waves hit the slope at a small grazing angle rather than at a more onshore-offshore angle, since the isobaths run primarily east-west). At these grazing angles of azimuthal incidence there is little change in onshore/offshore wavenumber upon reflection so that one would not see much enhancement of energy at the critical frequency. Gilbert (1993) also remarks on non-linear processes that could alter the expected (from linear theory) characteristics of reflected internal waves.

Gilbert's (1993) speculations are provocative. Many additional sites must be sampled however to sort out the competing processes. The available Hawaiian dataset is rich in topographic settings (i.e., slope magnitude and azimuth, and topographic curvature). Note also that an admitted uncertainty in Gilbert's (1993) work was his lack of accurate topography. This won't be a problem here as a digital bathymetric database has been constructed for the Hawaiian Is. under the support of ONR (e.g., see Keating, 1995).

APPROACH

For this initial exploratory investigation, in order to minimize the number of complicating factors, we chose to study the internal wave field near topographic features that are not proximal to continental shelves or strong mean currents, both of which could alter the characteristics of the internal wave field over a nearby sloping bottom. The Hawaiian Islands are a logical location for this investigation for two principal reasons. First, the islands are located in the middle of a Garrett and Munk (hereafter, GM) internal wave pool; that is, except perhaps very close to the surface and bottom boundaries, the ambient internal wave field surrounding the islands is expected to be well described by a canonical spectral model first popularized by Garret and Munk (1972, 1975) then refined by Cairns and Williams (1976), Muller et al. (1978) and others. This situation can be contrasted, for instance, to the east coast of the United States where the presence of the Gulf Stream may result in non-GM characteristics for the internal wave field just off the continental slope, so that delineation of changes to the internal wave field attributable to the slope may be more difficult to pinpoint independently from the wave-mean flow interaction effects.

Second, there have been numerous investigations of the current and temperature fields around the Hawaiian Islands for engineering purposes (sewage dispersion studies, telephone cable path surveys, etc.) which have resulted in large amounts of data recorded very near the island flanks (usually within 10-100m of the bottom), in many distinctly different topographic settings (e.g., concave vs. convex bottom curvatures) which have been acquired from local ocean technology companies over the past 5 years by the faculty of the University of Hawaii. These data had not been examined previously for extraction of the information they contain about the internal wave field. Our approach to achieving the objectives above was to produce statistical and spectral descriptions of the internal wave field from the Hawaiian data just described, documenting deviations from the GM paradigm, and then categorizing these deviations in terms of bottom slopes and curvatures (determined from high-resolution bathymetric surveys around the Hawaiian Islands), stratification variations (using the numerous stratification profile data that usually accompanied the engineering surveys noted above), critical frequency variations, etc.

WORK COMPLETED

We examined time series and calculated energy spectra of 256 separate records of horizontal currents and 143 separate records of temperature to evaluate data quality and appropriateness for this investigation. 66 records of horizontal currents and 25 records of temperature were discarded due to apparent instrumental errors, gaps, precision problems and so forth. The remaining data, some of which needed to be edited for bad points or gaps, comprise a total of over 92 years of currents from 31 distinct sites ranging in depth from 100m to 5500m. Most of the sites have data taken within 10 meters of the bottom, and nearly all have data taken within 100 m of the bottom, making this combined dataset quite valuable for examining internal wave behavior in the presence of a variety of bottom configurations.

A variety of environmental characteristics, upon which the internal wave reflection process was expected to depend, were quantified, e.g., bottom slope and curvature at each site were estimated from high resolution bathymetric datasets, mean buoyancy frequency and its variability were estimated from vertical profiles of temperature and salinity, and the mean critical frequency and its variability were estimated from these slopes and buoyancy frequencies per the equation under "OBJECTIVES."

We also calculated higher-level analysis products (e.g., rotary spectra, polarization, ellipse stability and orientation) to provide as complete characterizations as possible of the internal wave field. Horizontal coherence functions were calculated to look at along-slope and cross-slope propagation characteristics.

RESULTS

Our principal results are as follows:

(i) The magnitude of near-bottom enhancement, relative to the canonical GM spectrum, of the internal wave energy at the critical frequency spans a very large range from being almost nothing to being equal to that found at Fieberling Guyot (Eriksen, 1998) which is the largest enhancement that has ever been observed.

(a) The largest enhancements occur at frequencies that are not close to either the Coriolis frequency, f, or the buoyancy frequency, N. That is, the greatest enhancements are found at periods of 3-6 hours, well away from $1/f$ (O(30) hrs period at Hawaiian latitudes) or $1/N$ (period less than 1 hour, at most sites). We do not have an explanation yet for this behavior.

(ii) The width of the spectral peak of enhanced internal wave energy was often quite large, easily encompassing the internal tide. Yet the internal tide never appeared to be enhanced. This could result for instance if the internal tide was propagating more along-slope than cross-slope, and thus would have at most a glancing reflection from the boundary with minimal effect (this argument was proffered by Gilbert (1993) to explain weak enhancement near f on the continental slope south of Nova Scotia). In fact, the characteristics of most of the internal tides we observed suggest dominant along-slope propagation. The question as to why the internal tides should propagate dominantly along-slope was part of the motivation for the construction of a detailed numerical model of the internal tides around Oahu by one of us (MAM; see Lewis et al., 2000).

(iii) The cross-slope curvature of the bottom does not appear to have the simple correspondence to energy enhancement as postulated by Gilbert (1993), who surmised that a bottom profile with convex curvature would lead to greater energy enhancement at the critical frequency than concave bottom profiles. We find significant enhancement over convex and concave bottoms alike. Other factors besides bottom curvature must be important.

(iv) The amount of enhancement of energy at the critical frequency near bottom is highly variable over distances as short as 1 km. Some of these spatial differences appear to be related to general changes in the environment.

(a) From the west side of Oahu to the south side (in Mamala Bay) the enhancement at similar depths and similar slopes goes from very strong to weak. We believe this is due to a change in the ambient internal wave field. That is, the west side of Oahu descends uniformly down to the ocean floor, while the Mamala Bay sites are inshore of a broad, 500 m deep platform. We believe this "shoal" may be filtering out energy from the open ocean internal wave field before it can interact with the inshore boundary. To test this hypothesis will require the collection of new datasets of currents and temperatures from the deep ocean onto the "shoal" in Mamala Bay. Anecdotally, Pinkel (2000, private communication) observed a dramatic reduction in internal wave activity in current shear, derived from a new deep-penetration ADCP, inshore of the 500m isobath at the end of a research cruise from San Diego to Honolulu. [Note that the reduction of internal wave energy from the deep ocean onto the shallow continental shelves is well known, e.g., Levine (1999).]

(b) A more perplexing spatial variation in the critical frequency enhancement was observed in the Alenuihaha Channel between Maui and the island of Hawaii. At similar depths and slopes, but opposite sides of the channel (10 km distance), the critical frequency enhancement is either strong with a narrow peak or weak with a broad peak. We speculate that these differences may be due to differing bottom morphologies, i.e., where the enhancement is weak and broad in frequency the bottom is apparently "rougher". More data will be needed to confirm or reject this speculation.

(v) We have found no deviation from the linear prediction that the current ellipses should be oriented across isobaths at the critical frequency. The stability of the orientation of the current ellipse as frequency varies across the critical frequency bands suggests that Rhines' (1970) trapped modes are not present. Neither do we find unidirectional along-slope propagation, as would be expected if Rhines' modes were present.

(vi) Where data is available from compact arrays we find high cross-slope coherence right at the critical frequency with phase lag corresponding to upslope propagation. This result is consistent with the idea that the reflection process dramatically narrows the wavenumber bandwidth of the internal wave field. What remains to be determined is whether the observations show evidence of the turbulent layer predicted by the numerical model experiments of Slinn and Riley (1996, 1998). The turbulent layer should also exhibit high upslope coherence with upslope phase propagation.

IMPACT/APPLICATION

The result, logical in retrospect, that the internal wave energy levels around the critical frequency vary substantially over short distances suggests that accurate models (e.g., the Internal Wave Action Model;
http://www.soest.hawaii.edu/oceanography/workshops_html/muller_iwam.html) of internal wave energy near topography (as might be needed for acoustic propagation models and models of diapycnal mixing) will require accurate local bathymetric data, and possibly

morphological data, as well as consideration of the broader environment (e.g., the existence of nearby shoals that may attenuate the open ocean internal wave field). Not all factors that affect the critical frequency reflection process have been identified yet, which suggests that such modeling efforts will be somewhat futile for the foreseeable future.

RELATED PROJECTS

Some of the early results from this project were used in the design of an experiment (the Hawaii Ocean Mixing Experiment - HOME; Luther et al., 1999; http://chowder.ucsd.edu/home/) that has been funded by the National Science Foundation to study the role of topography in catalyzing sub-thermocline mixing. Both Luther and Merrifield are co-PIs on HOME, which includes over 25 co-PIs and is led by R. Pinkel (SIO). The principal focus of this experiment is on the role of internal tides in producing the enhanced mixing, but the existence of alternative sources of energy for mixing (such as from the high shear generated by higher than normal levels of energy around the critical frequency) have to be acknowledged and considered. Parts of the HOME field work will collect data that will be quite useful for looking at the characteristics of the internal wave field near the boundary.

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14. ABSTRACT

The reflection of oceanic internal waves at the sloping flanks of the Hawaiian Islands has been examined with historical records of current, temperature, stratification and bathymetry. The characteristics of the reflection process at the so-called "critical frequency" were sought as a function of environmental parameters. Dramatic spatial variations in the strength of the internal wave field at the critical frequency near topography were found, with the most important environmental factors being buoyancy frequency, bottom slope, direction of propagation of incident waves, proximity to shoals, and possibly bottom morphology. Contrary to the published literature, bottom curvature was not an important factor.

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